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## THE FORMATION PROCESS OF THE He I $\lambda$ 10830 LINE IN COOL GIANT STARS

NAME AND ADDRESS OF  
INSTITUTION:

Iowa State University  
Ames, Iowa 50011

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Dr. Donald G. Luttermoser  
Iowa State University

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Final Technical Report (NAG 5-1655) covering 7/01/91 – 6/30/93.

The Formation Process of the He I  $\lambda 10830$  Line in Cool Giants

Donald G. Luttermoser, P.I. (Iowa State University)

This NASA grant covers my research program, which involves observing a sample of cool giant stars with ROSAT. These stars were selected from the list of bright stars which display He I  $\lambda 10830$  in absorption or emission and lie on the cool side of the coronal dividing line. With measured X-ray fluxes or upper limits measured by the PSPC, we investigated the role X-rays play in the formation of this important line using the non-LTE radiative transfer code PANDORA. Hydrodynamic calculations have been performed to investigate the contributions of acoustic wave heating in the formation of this line as well.

## 1 Introduction

Linsky & Haisch (1979) determined that the cool side of the H-R diagram is divided into 2 distinct regions: (1) F-M dwarf and late F through early K giants, which show evidence for chromospheric ( $T \leq 20,000$  K) and higher  $T$  ( $5 \times 10^4 - 2 \times 10^5$  K) gas through emission lines seen in IUE spectra, and have been coined *coronal stars*; and (2) Single red giants later than K2 III and supergiants later than G5 Ib, which have generally weaker chromospheric emission and no evidence for higher  $T$  species — the so-called *non-coronal stars*. The “line” that separates these regions has been coined the *Coronal Dividing Line* (CDL). Ayres *et al.* (1981) confirmed the CDL with *Einstein* observations at X-ray wavelengths. Stars on the cool side of the CDL also show evidence for massive stellar winds ( $10^{-8} - 10^{-5} M_{\odot} \text{ yr}^{-1}$ , Stencel & Mullan 1980). These observations have lead to the suggestion that a “mechanical” energy input on the hot side of CDL heats gas to temperatures greater than  $10^6$  K, and that a mechanical energy flux on the cool side of CDL drives strong stellar winds.

Coronal stars are thought to be solar-like with: (1) Chromospheric layers where

$$\frac{F_{\text{mech}}}{dh} > 0, \quad \frac{dT}{dh} > 0, \quad T \sim 10^4 \text{ K}$$

and

$$h_{\text{corona}} > h > h_{\text{photo}},$$

which give rise to emission features in singly ionized resonance lines (*i.e.*, Ca II H & K, Mg II h & k, Fe II). The strength of ionized emission features have been noted to be correlated with  $\vec{B}$ -field strength (see Schrijver 1991). This suggests that acoustic heating of sound waves from the convection zone of these stars is modified (somehow) by magnetic fields. (2) Transition Region (TR) layers where

$$\frac{F_{\text{mech}}}{dh} > 0, \quad \frac{dT}{dh} \gg 0, \quad T \sim 10^5 \text{ K}$$

and

$$h_{\text{corona}} > h > h_{\text{chromo}},$$

which give rise to emission features in doubly- and triply- ionized resonance lines (*i.e.*, C IV  $\lambda 1550$ ).

(3) Coronal layers where

$$\frac{F_{\text{mech}}}{dh} > 0, \quad \frac{dT}{dh} \sim 0, \quad T \sim 2 \times 10^6 \text{ K}$$

and represent the uppermost layer, which give rise to emission features of highly ionized species at X-ray wavelengths and show a definite correlation between X-ray flux and  $\vec{B}$ -field strength.

Meanwhile, non-coronal stars have no evidence of magnetic field influence, but instead have evidence for: (1) Chromospheric layers which give rise to emission features in singly ionized resonance lines; and (2) a wind region. Much debate has ensued over the characteristics of the chromospheres in these late-type stars. Are they solar-like, a hydrodynamic chromosphere or “calorisphere” (Bowen 1988; Willson 1988; Dupree *et al.* 1990; Luttermoser & Bowen 1992), or possibly a post-shock region (Bowen 1988; Luttermoser & Bowen 1990)? There is also considerable discussion concerning the mechanism that drives the winds of these stars. Possibilities include radiation pressure on dust, molecular levitation (Elitzer *et al.* 1989), and shock propagation and merging (Bowen 1988; Cuntz 1992).

Stars on the “hot” side of the CDL display He I ( $2s\ ^3S - 2p\ ^3P^o$ ) triplet lines near 10830 Å that are broad, shallow, and constant, similar to  $\beta$  Gem (O’Brien & Lambert 1986). The formation of this *chromospheric* multiplet in these stars is controlled by *backflowing* coronal EUV and X-radiation. Lambert (1987) has shown that stars on the “cool” side of the CDL show variable He I  $\lambda 10830$  features — sometimes going into emission! With this grant, we wished to answer the question: “How is this line formed in the non-coronal stars?”

*Einstein* detected no X-rays from nearby K-giants  $F_X < 0.01F_X(\odot)$  (Ayres *et al.* 1981). The ROSAT observations of this program and others have pushed this limit to  $F_X < 0.001F_X(\odot)$  for  $\alpha$  Tau (Luttermoser 1994) and  $F_X < 0.0001F_X(\odot)$  for  $\alpha$  Boo (Ayres *et al.* 1991). Should this flux be too low to produce the observed He I  $\lambda 10830$  feature via photoionizations, one would need  $T > 40,000$  K gas for collisional excitation to populate the  $2s\ ^3S$  state as shown in Figure 1 (Cuntz & Luttermoser 1990). Stochastic shocks formed by the propagation of short period acoustic waves into the tenuous layers of the outer atmosphere are a likely scenario (Cuntz 1987).

## 2 ROSAT Observations of $\alpha$ Tau & $\alpha$ Cas

Two stars *just* on the “cool” side of the CDL (see Figure 2) were selected as a test case in understanding He I  $\lambda 10830$  formation in these types of stars. The star  $\alpha$  Cas is classified as K0 II–III (*i.e.*, a 4700 K star at a luminosity class between bright giant and giant). It has an apparent, integrated-bolometric flux  $\ell_{bol} = 4.6 \times 10^{-6}$  erg cm $^{-2}$  s $^{-1}$  and  $d = 63$  parsecs. Meanwhile,  $\alpha$  Tau is a K5 III (*i.e.*, 4000 K giant) star with  $\ell_{bol} = 3.6 \times 10^{-5}$  erg cm $^{-2}$  s $^{-1}$  and  $d = 20$  parsecs. These stars both show He I  $\lambda 10830$  lines. This line in  $\alpha$  Cas has  $W_\lambda = 230$  mÅ and is constant in strength similar to  $\beta$  Gem (Lambert 1987). In  $\alpha$  Tau, it varies in strength from no line to  $W_\lambda = 37$  mÅ. It was not observed in emission however as is the case for some non-coronal K giants (O’Brien & Lambert 1986).

IUE observations have suggested that both of these stars have chromospheres but no coronae (see Ayres *et al.* 1981). For  $\alpha$  Cas:  $f_{MgII}/\ell_{bol} = 8.2 \times 10^{-6}$  with no apparent emission in C IV or He II ( $\lambda 1640$ ). For  $\alpha$  Tau:  $f_{MgII}/\ell_{bol} = 4.8 \times 10^{-6}$  with no apparent emission in C IV or He II. For reference, the known coronal star  $\beta$  Cet (K1 III) has  $f_{MgII}/\ell_{bol} = 2.6 \times 10^{-5}$ ,  $f_{CIV}/\ell_{bol} = 1.0 \times 10^{-7}$ ,  $f_{HeII}/\ell_{bol} = 1.1 \times 10^{-7}$ .

The *Einstein* observations by Ayres *et al.* (1981) did not detect any X-ray flux for  $\alpha$  Cas or  $\alpha$  Tau. Upper limit for  $\alpha$  Cas were  $f_X/\ell_{bol} < 3.0 \times 10^{-8}$  and for  $\alpha$  Tau were  $f_X/\ell_{bol} < 4.0 \times 10^{-9}$ . For reference,  $\beta$  Cet has  $f_X/\ell_{bol} = 4.0 \times 10^{-6}$ . The K0 III star  $\beta$  Gem, for which the He I  $\lambda 10830$  line does not vary, has  $f_X/\ell_{bol} = 4.0 \times 10^{-8}$ , and represents the weakest coronal X-ray emitting giant star seen by *Einstein*.

In order to understand the mechanism of the formation of the He I  $\lambda 10830$  feature for stars on

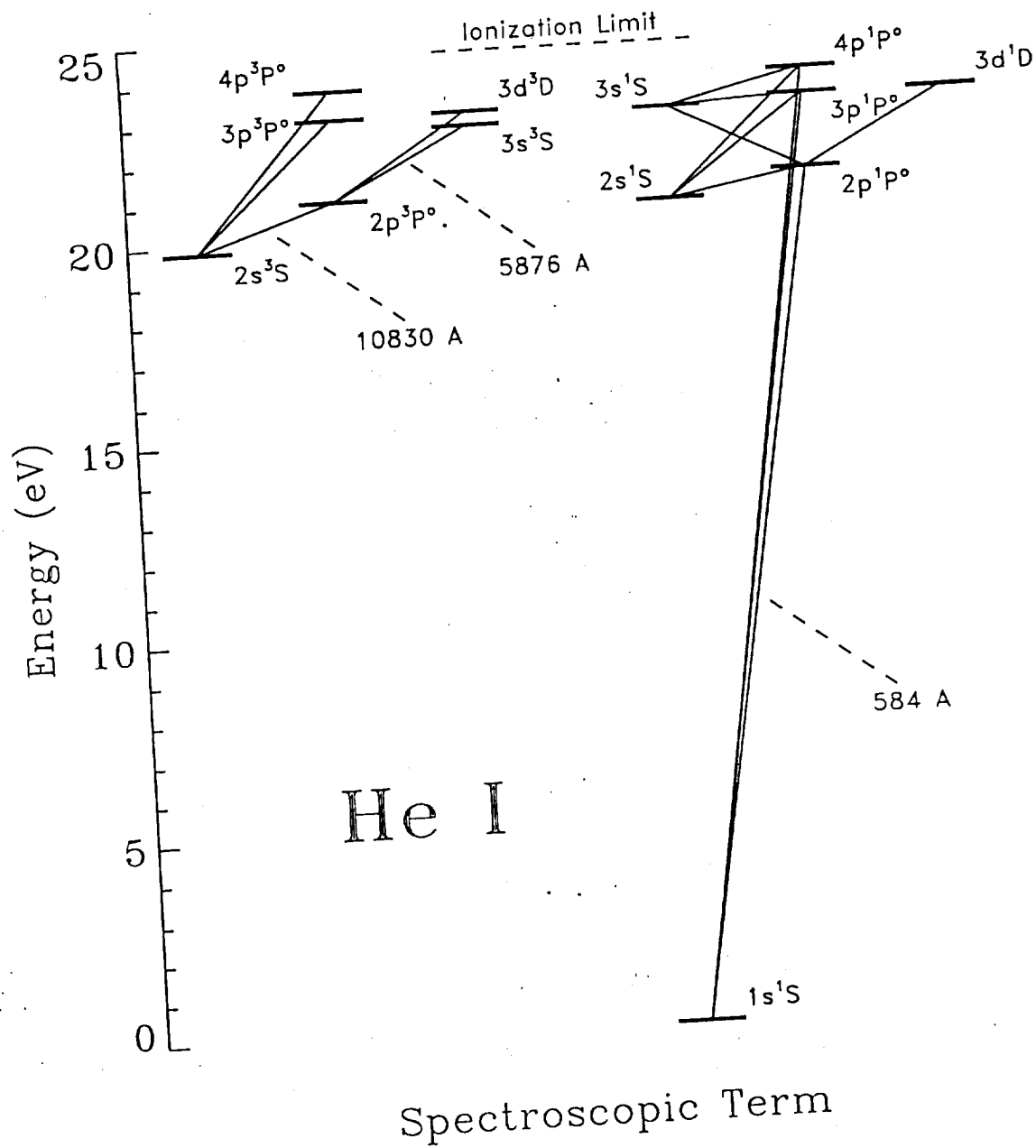


Figure 1: Electronic structure of He I. Note that the lower state of the  $\lambda 10830$  multiplet is a metastable state.

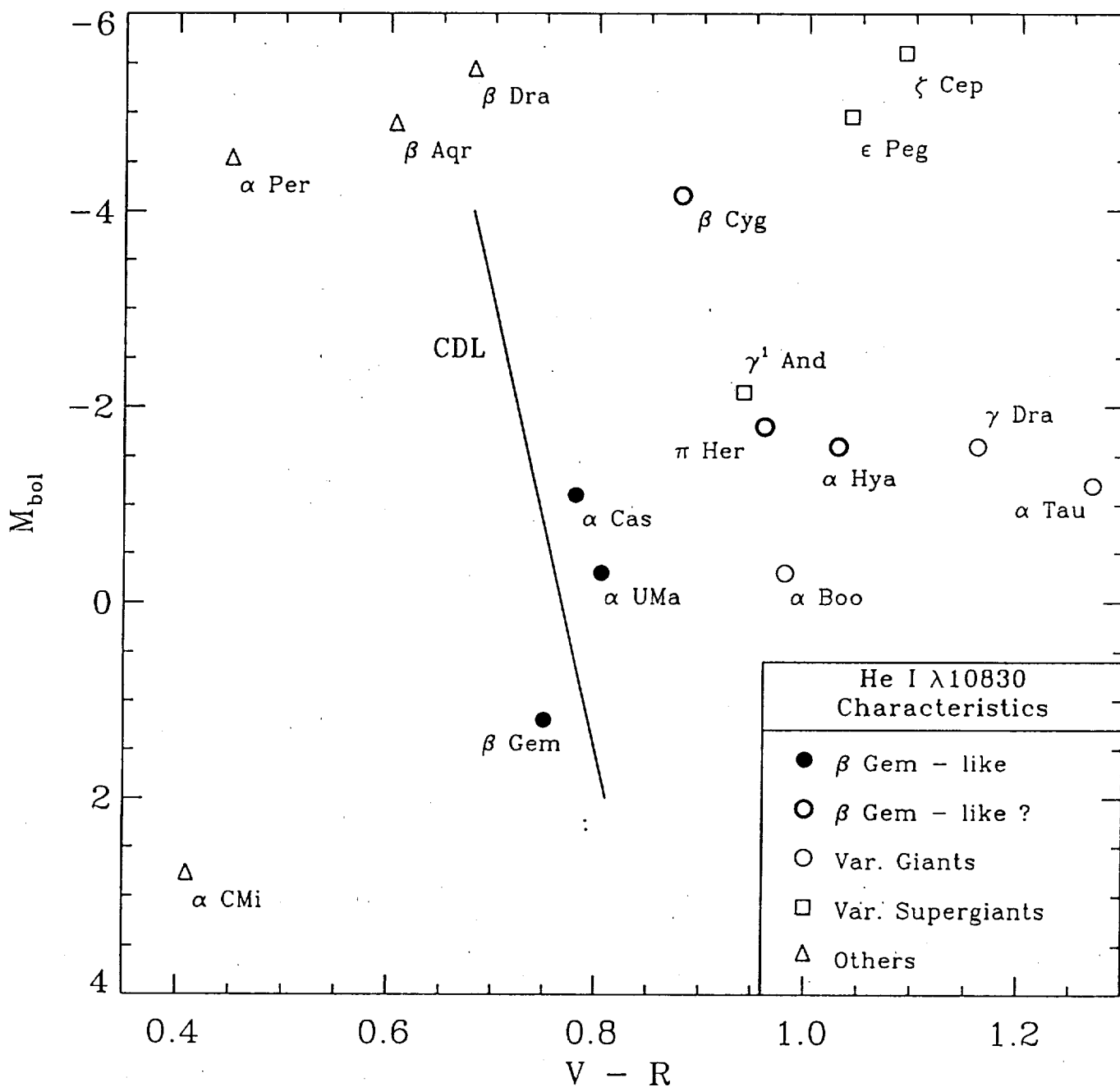


Figure 2:  $M_{bol}$  vs.  $V - R$  diagram for a sample of stars near the CDL. Our target stars  $\alpha$  Cas and  $\alpha$  Tau are indicated. Note that  $\alpha$  Cas is on the “non-coronal” side of the CDL yet has a He I  $\lambda 10830$  signature similar to a “coronal” star.

the cool side of the CDL, we had to first push down the *Einstein* upper limits of the X-ray flux for these stars. During ROSAT's 1st and 2nd years, the PSPC (Position Sensitive Proportional Counter) obtained data over 3 separate pointings for  $\alpha$  Tau on 24 February 1991 (Figure 3) over a total of 6833 seconds, and  $\alpha$  Cas on 7 January 1992 (Figure 4) over a total of 5897 seconds. The PSPC has an energy range of  $\sim 0.1$ – $2.4$  keV ( $124$ – $5$  Å) and a modest degree of energy resolution ( $\Delta E/E \approx 0.5$ ) (see Trümper 1983). The PSPC did not detect  $\alpha$  Tau in 7 ksec (note that Tom Ayres did not detect  $\alpha$  Boo (K1 III) in 18.6 ksec).

Using IDL reduction software developed by Dr. Fred Walter, the new X-ray flux upper limit for  $\alpha$  Tau is  $2.08 \times 10^{-15}$  erg cm $^{-2}$  s $^{-1}$ , which is based on the  $3\sigma$  upper limit of 4.8 counts. This corresponds to  $f_X/\ell_{bol} < 5.78 \times 10^{-11}$  (a factor of 70 improvement to the *Einstein* upper limit). Previously undetected in X-rays, this program discovered  $\alpha$  Cas to be a weak X-ray source! The net extracted source count is  $56.6 \pm 8.7$  during this observation. This corresponds to  $f_X = 2.46 \times 10^{-14}$  erg cm $^{-2}$  s $^{-1}$  (note that the *Einstein* upper limit was  $1.38 \times 10^{-13}$  erg cm $^{-2}$  s $^{-1}$ ). Also,  $f_X/\ell_{bol} = 5.35 \times 10^{-9}$  (6 times lower than the *Einstein* upper limit). Hence  $\alpha$  Cas is actually a coronal star (as the He I already suggested)! The CDL must be moved to the right (slightly) in the bright giant regime.

### 3 He I Calculations

He I  $\lambda 10830$  synthetic spectra are generated with the PANDORA stellar atmospheres code both with and without the external (i.e., *coronal*) X-ray field. PANDORA solves the radiative transfer and statistical equilibrium equations in a self-consistent manner with the equivalent 2-level approach (see Vernazza, Avrett, & Loeser 1981). Calculations can be made in either plane-parallel or spherically-symmetric geometries as either a semi-infinite atmosphere or a finite slab. Macroscopic gas velocity fields can be incorporated into the line source function, line profile, and net rate equation calculations. External radiation fields incident on the atmosphere can be included in the calculations.

By comparing the various calculations, the influence of a *coronal* X-ray flux on the He I triplet can be explored. We follow the procedure described by Avrett *et al.* (1976) and Cuntz & Lutermaier (1990) to calculate the excitation and ionization of helium. The photoionization rate is given by

$$R = 4\pi \int_{\nu_1}^{\infty} \frac{\alpha(\nu)}{h\nu} J_{\nu} d\nu,$$

$\alpha(\nu)$  is the photoionization cross section and  $J_{\nu}$  is the mean intensity of both the photosphere/chromosphere radiation field and the external X-radiation field deduced from the ROSAT observations.

The following radiative transfer calculations are made in sequence with output from the preceding used as input for the next stage. (1) A 3-level hydrogen model atom is used in a static, plane-parallel medium. H $\alpha$  is treated explicitly and Ly- $\alpha$  and Ly- $\beta$  are assumed to be in detailed balance. Balmer and Paschen photo-ionization rates are approximated with an input radiation temperature. (2) A 5-level hydrogen atom is used in a static (and where appropriate, dynamic), spherically symmetric medium. All transitions are handled in detail. (3) The following species will first be calculated assuming a static, plane-parallel medium and second (where appropriate) a dynamic, spherically symmetric medium: C I (9-levels), C II (7-levels), O I (13-levels), Mg I (7-levels), Mg II (6-levels), Ca I (8-levels), and Ca II (5-levels). (4) A 13-level neutral helium atom and a 6-level singly ionized helium atom for both a plane-parallel and spherically symmetric medium. All photoionizations and recombinations to the given levels are included. Upon convergence of the radiative transfer and statistical equilibrium equations with PANDORA, He I  $\lambda 10830$

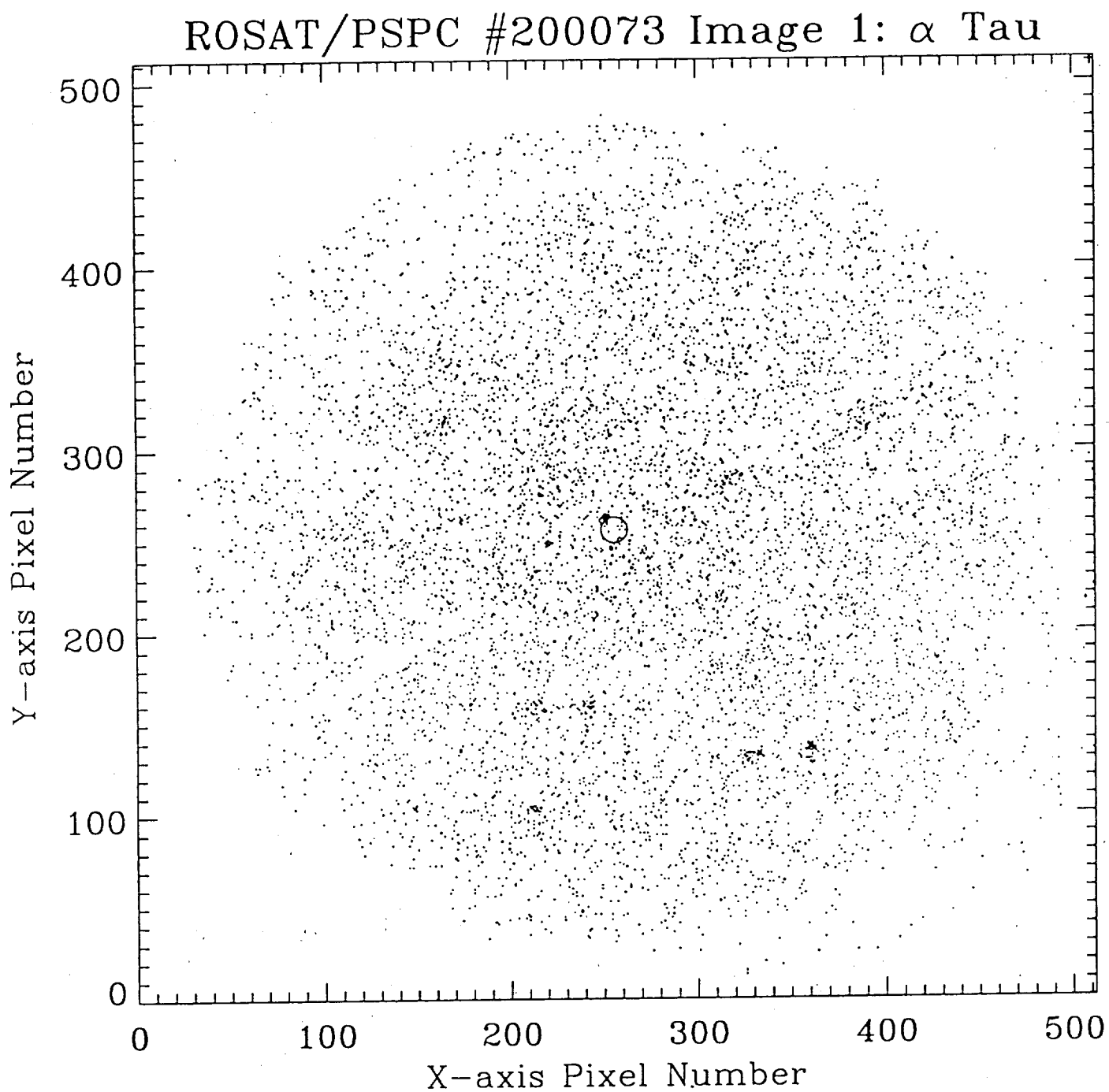


Figure 3: PSPC image with an exposure time of 6.8k sec of the  $\alpha$  Tau region.



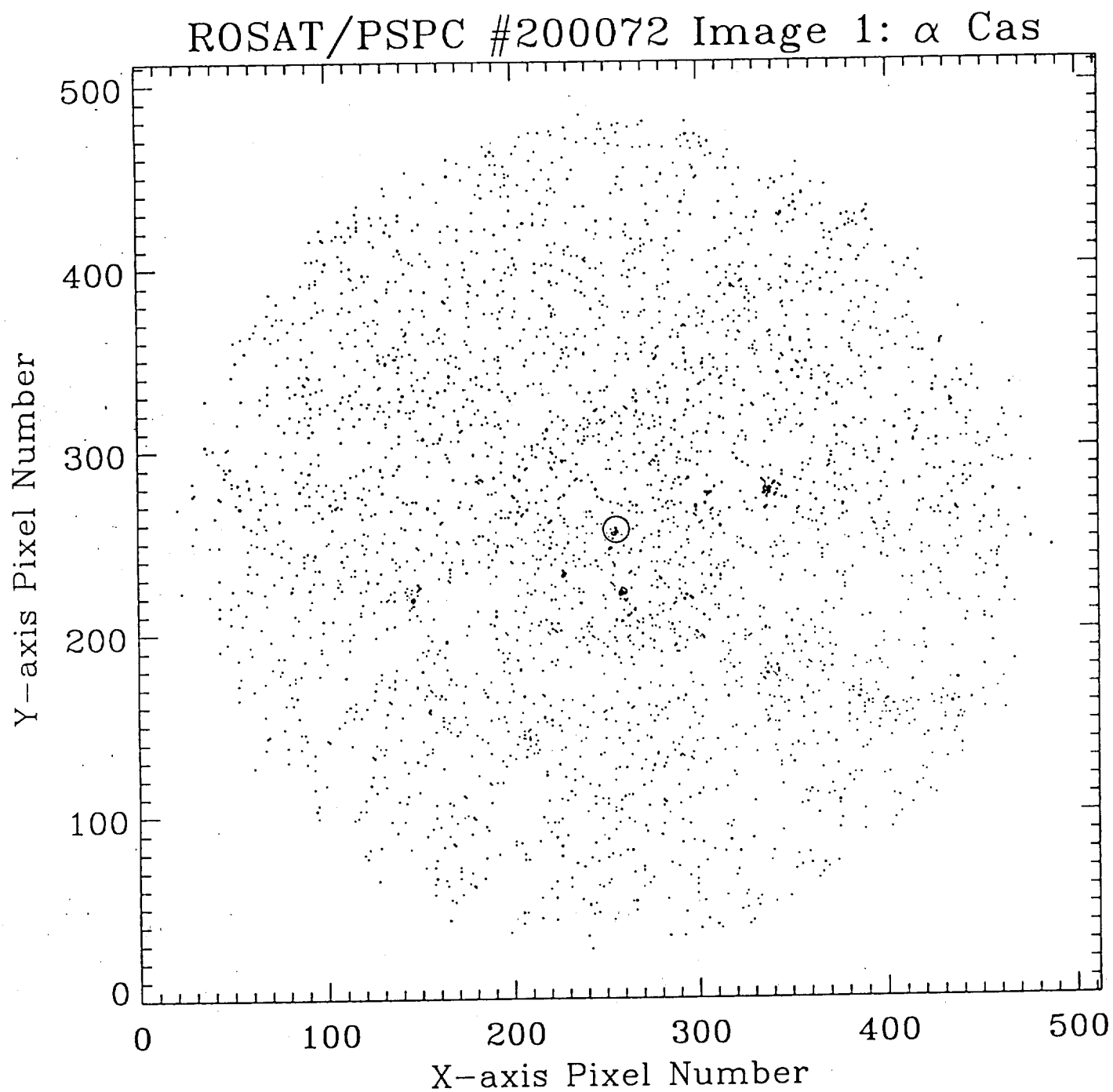


Figure 4: PSPC image with an exposure time of 5.9k sec of the  $\alpha$  Cas region.

synthetic line profiles from semi-empirical models (with and without X-ray fluxes included) are compared to the observations of O'Brien and Lambert (1986) and Lambert (1987). These comparisons are a strict test for the X-ray photoionization process in the formation of He I  $\lambda 10830$  in these cool giants.

The test of the photoionization method is to produce He I  $\lambda 10830$  with  $W_\lambda \approx 230$  mÅ for  $\alpha$  Cas and  $\approx 20 - 30$  mÅ for  $\alpha$  Tau. The incident X-radiation field must not affect the H Balmer lines. Must also not affect any other chromospheric emission features (*i.e.*, Mg II h & k and Ca II H & K). With the upper limit set by ROSAT for  $\alpha$  Tau, assuming an ISM hydrogen column density of  $8.2 \times 10^{19}$  cm $^{-2}$  and a Raymond-Smith X-ray spectrum, **no He I feature formed** in our representative chromospheric model of  $\alpha$  Tau (Kelch *et al.* 1978). The ROSAT X-ray flux measured for  $\alpha$  Cas produced a He I  $\lambda 10830$  feature at 210 mÅ (with  $N_H = 2.6 \times 10^{20}$  cm $^{-2}$ ), which is close to the observed value for this star (see Figure 5)!

## 4 Can Stochastic Shocks Produce He I $\lambda 10830$ ?

Since the new  $f_X$  upper limits set by ROSAT for the non-coronal stars are too low to produce He I  $\lambda 10830$ , we need some other process to form this feature. Cuntz & Luttermoser (1990) have shown that a 2nd method can give rise to the He I feature. Stochastic shocks can heat the gas in the outer regions of these stellar atmospheres to  $T \geq 40,000$  K, where sufficient numbers of electrons can be pumped to the  $2s\ ^3S$  metastable state ( $\sim 20$  eV). Cuntz (1987) has shown that the dissipation of mechanical wave energy leads to an increase of the mean atmospheric temperatures to chromospheric values in the outer layers. Either periodic or non-periodic waves can be modeled, where the non-periodic waves change stochastically over a short period.

A non-periodic wave model of Arcturus (Cuntz 1987) shows a quite interesting behavior. Due to the stochastic change of the wave periods, shocks with different strengths are produced. The speeds of these shocks are usually different which leads to an overtaking and merging of shocks. Since an overtaking shock has a combined strength and therefore an increased speed, it overtakes more and more shocks in front of it and attains a very large strength. Such a phenomenon is called *shock merging*.

The momentum transfer of these strong shocks cause episodic mass loss. Furthermore, the energy dissipation of the strong shocks produce high temperatures in the post-shock regions. Occasionally,  $T > 40,000$  K are reached. Stochastic acoustic wave models for the chromospheres of late-type giant stars could lead to a possible explanation for the presence of the He I  $\lambda 10830$  line. The highly variable He I profiles in the non-coronal K giants are strong evidence for the presence of atmospheric outflows and inflows. The stellar wind flows in the stochastic wave models of Cuntz often show the same behavior.

Cuntz & Luttermoser (1990) have carried out a series of NLTE radiative transfer calculations for He I based on hydro models representative of the archetypical, non-coronal star  $\alpha$  Boo. We were able to produce He I profiles at the proper strength! We had some rather focused requirements: we needed shocks at  $T > 40,000$  K that are **not too low** in the atmosphere ( $h \approx 2 \times 10^6$  km above the visual-continuum formation depths) so that H, Mg II, & Ca II are unaffected. We also needed shocks at  $T > 40,000$  K that are **not too high** ( $h \approx 3 \times 10^6$  km above the visual-continuum formation depths) so that densities are high enough to allow sufficient collisional excitations to populate the  $^3S$  state. It was found that radiative transfer effects in a moving medium weaken this line with respect to the static calculations. We were unable to produce any He I emission at any phase. This lead us to the speculation that long period acoustic waves are also needed in the hydrodynamic calculations.

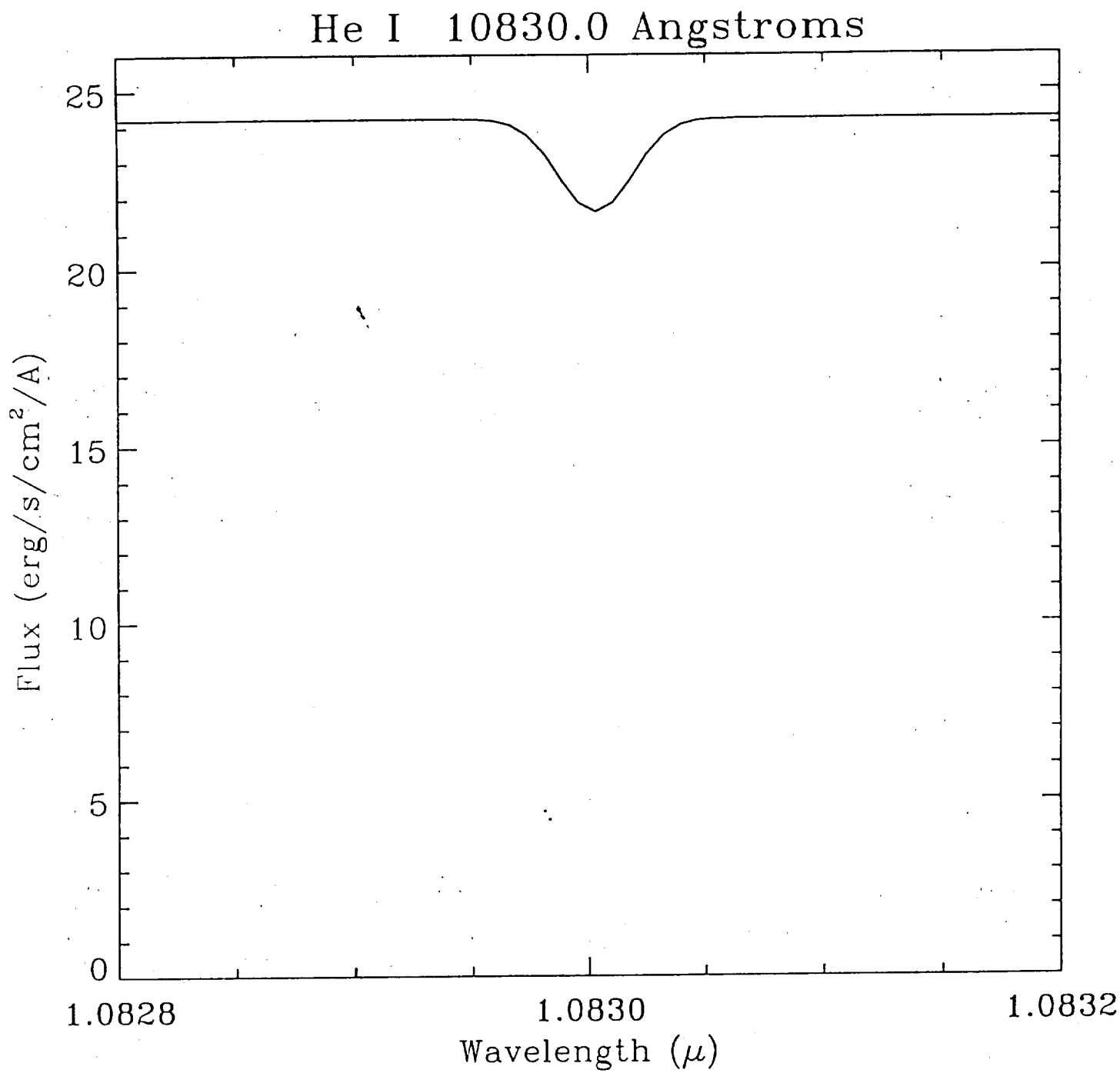


Figure 5: He I  $\lambda$ 10830 line for the  $\alpha$  Cas model irradiated by the X-ray flux as measured by ROSAT for this star.

## 5 Conclusions

To summarize, this ROSAT program has resulted in the X-ray detection of a previously classified *non-coronal star*! This detection of  $\alpha$  Cas corresponds  $F_X = 0.002 F_X(\odot)$  and is sufficient to form the He I  $\lambda 10830$  feature in this star. The CDL must be moved to the right on the H-R diagram in the bright giant regime! Upper limit to the X-ray flux of  $\alpha$  Tau has been reduced by a factor of 70 over the *Einstein* value. This flux is insufficient to populate the  $^3S$  state, hence He I feature seen in this star cannot arise from the photoionization mechanism. The He I feature in the *non-coronal* stars can be formed by stochastic shocks propagating through their atmospheres. This work has been presented in a paper that has just been submitted to the *Astrophysical Journal*.

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